Red VCSELs for POF Data Transmission and Optical Sensing Applications

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Abstract

We have fabricated VCSELs in the visible red spectrum. The emission wavelength ranges from approximately 650nm to 690nm depending on application. The devices are grown on GaAs substrates by MOVPE and processed using standard VCSEL processing technology. The active layer consists of three InGaP quantum wells. The Bragg mirrors are AlGaAs/AlAs multilayer structures. The bottom mirror is n-doped, the top mirror is p-type doped. The threshold current of the devices is less than 2mA. The maximum operating temperature is beyond 60^{o}C. The optical output power is limited by eye-safety conditions to a maximum of 390µW. The modulation bandwidth of the devices is in excess of 3GHz even for low operating currents below 5 mA. This enables IEEE1394b S800 and Gigabit Ethernet transmission speed over POF as well as higher speed applications such as optical links for high definition TV.

Any real application requires highly reliable devices and hence intensive life time testing of these red VCSELs has been undertaken. From aging test results applying various operating temperatures and currents we have inferred a conservative estimate for the activation energy of 0.6eV. The 1%-time-to-failure (1%TTF) of the devices is over 100,000 hrs at use conditions. Continuous testing of more devices over thousands of operating hours is poised to improve reliability data further.

Introduction

Red VCSELs are interesting light sources for various data transmission and optical sensing applications [1]. Plastic optical fiber (POF) has gained tremendous interest in recent years for very low cost optical interconnects. The automotive industry consumes more than 10 million POF transceiver modules per annum for the in-car infotainment system [2]. Home networking and in particular Ethernet connections for IPTV is another high volume application for this emerging POF technology [3, 4].

Current transmitters are based on conventional red LEDs or higher speed Resonant Cavity LEDs (RCLEDs) emitting at around 650nm where standard POF exhibits a minimum in optical attenuation. However, higher speed communication systems in the Gb/s range require laser technology at 650nm to provide the necessary bandwidth. Conventional DVD type lasers tend to be too noisy and are not compatible with low cost plastic packaging technologies. On the other hand red VCSELs emitting in the 650nm range are almost ideal components for very low cost, short distance and high speed optical interconnects for consumer applications.

Visible VCSELs also offer great advantages for optical sensing applications because the user of the device can see the light. This is a clear advantage in terms of eye safety and for aligning the optical beam by non-laser specialists. We have fabricated single mode VCSELs that show a Gaussian-type circular far-field pattern with high beam quality. This results in a homogenous illumination of the optical sensing target area. The divergence angle is only 8 degrees FWHM. The beam can in most cases be easily collimated using low cost plastic optics. The single mode beam emission also shows up as a highly pure spectrum with a large coherence length. This is useful for various sensor systems including the optical mouse and other consumer electronics related applications.

Red VCSEL Design

The red VCSELs are based on GaAs substrates. Multilayer stacks of AlGaAs are grown on the substrate by MOVPE to form the Bragg mirrors and the active layer. Figure 1 shows a cross-section of the device. The mirrors consist of alternating quarter-wave layers of $Al_xGa_{1-x}As$ and $Al_xGa_{1-x}As$ where x varies between 0.5 and 0.95. The bottom mirror is made of 55 pairs and is n-type doped, the top mirror counts 35 layer pairs and is p-type doped. The active layer contains three compressively strained InGaP quantum wells embedded in InAlGaP barriers of larger bandgap energy. The entire cavity is one optical wavelength long. Standard VCSEL processing includes mesa etching, aperture forming, metallization for p-type and n-type contacts. The active diameter is typically between 4µm and 8µm for single mode devices and slightly larger for higher power multimode VCSELs.

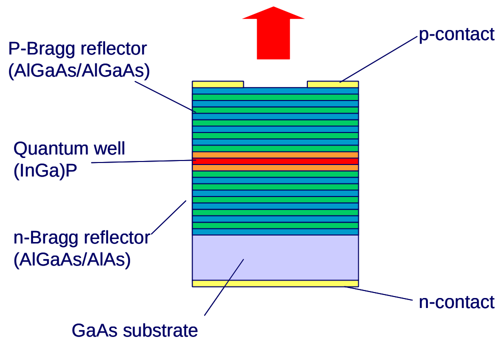


Fig. 1: Red VCSEL structure showing the Bragg reflectors and the active quantum wells embedded in there

Emission Characteristics

Figure 2 shows the light output versus drive current characteristics of a single-mode VCSEL emitting at 665nm. The maximum power for this particular device is almost 1mW at room temperature. The maximum power decreases with increasing temperature to 0.2mW at 60°C. The high temperature performance is limited by the relatively small conduction band offset of the InAlGaP active material system. DVD lasers and other red sources exhibit similar properties.

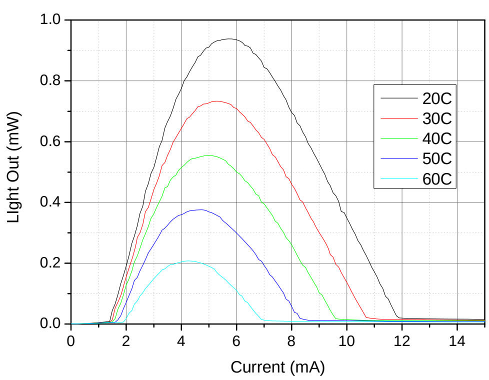


Fig. 2: Light output current characteristics of red VCSEL emitting at 665nm for various ambient temperatures. The device can operate to above 60°C

The visible light emission can be seen with the naked eye. Therefore any alignment in applications such as optical sensing or free space data transmission is much easier to accomplish as compared to infrared lasers. Figure 3 depicts the red light emission of a VCSEL mounted in a TO-can.

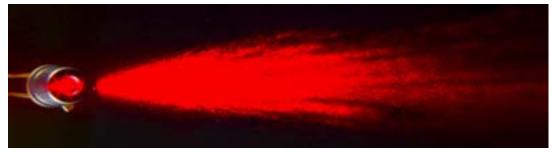


Fig. 3: Red VCSEL mounted in TO-can showing visible light output

The single mode VCSELs exhibit a large side mode suppression ratio of more than 20dB. Since the devices heat up during operation the spectra shifts to the longer wavelength with increasing drive current. Figure 4 shows spectra for a device emitting around 680nm for different driver currents. The lasing mode also shifts to longer wavelengths with increasing ambient temperature. The thermal wavelength shift is 0.04nm/K.

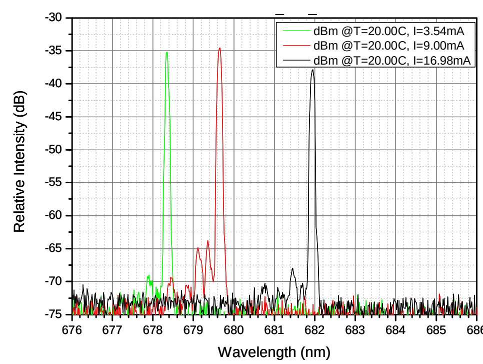


Fig. 4: Spectra of single mode visible VCSEL emitting around 680nm for different drive currents. The thermal shift with temperature is only 0.04nm/K

The VCSEL structure is grown on slightly off-axis substrate material. Therefore the optical gain in the active layer is non-isotropic in the plane of the layer structure. The non-isotropic gain results in a highly polarized optical emission. Figure 5 shows the polarization resolved light current characteristics of a VCSEL. The lasing light output is entirely parallel to one crystal axis. The perpendicular axis shows only a small amount of spontaneous light emission.

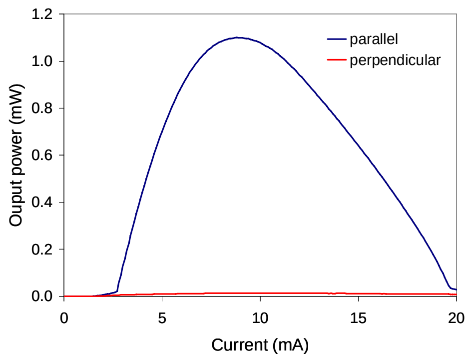


Fig. 5: Polarization resolved light output current characteristics of a red VCSEL. These VCSELs always lase in a single polarized mode due to gain an-isotropy in the active layer

Figure 6 shows the high degree of polarization in the emission spectra of a particular device. The device lases in a single transversal and longitudinal mode. In addition, the spectra show a high mode suppression ratio between the two polarization states of more than 20dB. This makes the red VCSEL a truly single mode laser.

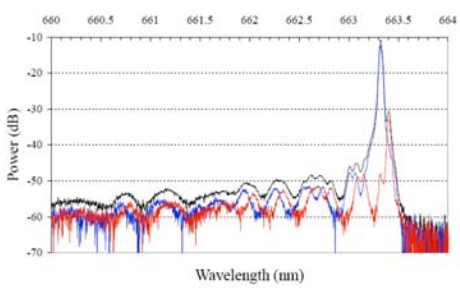


Fig. 6: Polarization resolved spectra showing high side-mode suppression ratio of more than 20dB

This behavior is quite different from standard 850nm VCSELs. These VCSELs tend to lase in both polarization states. The single polarized output of the red VCSEL described here is very beneficial for all applications free space optical elements or optical recording or any interference type application.

Another interesting parameter in particular for free space applications is the far-field pattern of the VCSEL. Figure 7 depicts the typical far-field of the red VCSEL for various drive currents.

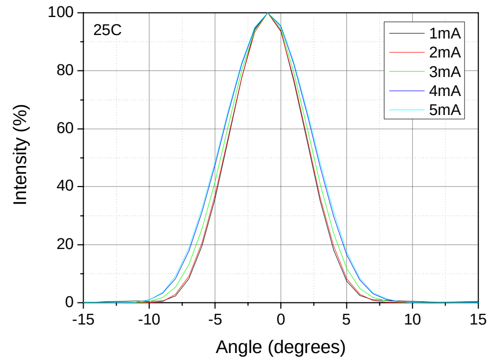


Fig. 7: Far field for different drive currents at room temperature

The far-field is round and highly symmetric. The full-width-half maximum (FWHM) angle is less than 8degrees. The small far-field angle is advantageous for the design of optical elements such as lenses. A collimating lens can be quite small with large alignment tolerances. This is a great advantage in comparison to edge emitting lasers where the FWHM emission angle is about 40degree in vertical direction.

High Speed Performance

The red VCSELs described in this paper are ideal light sources for high speed short distance optical links using plastic optical fiber (POF).

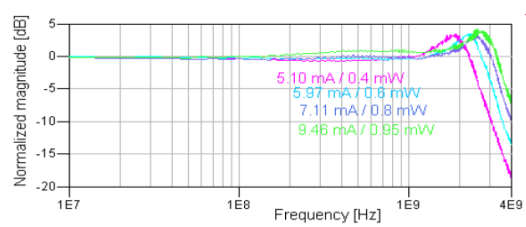


Fig. 8: Small signal modulation characteristic of red VCSEL for various bias currents

Data rates up to 250Mb/s can be obtained with RCLEDs as optical light source in the transmitter. Higher data rates require laser speed. Figure 8 shows the small signal modulation characteristics of a red VCSEL for various bias currents. The 3dB modulation bandwidth is around 3GHz. This enables high speed signal modulation of the red VCSEL.

The diagram (Fig 8) indicates that the relatively high modulation frequency is obtained even at low bias currents of less than 10mA. The low current consumption allows a very compact packaging of the devices. Figure 9 depicts the leadframe style package used for the VCSEL in high speed POF interconnects.

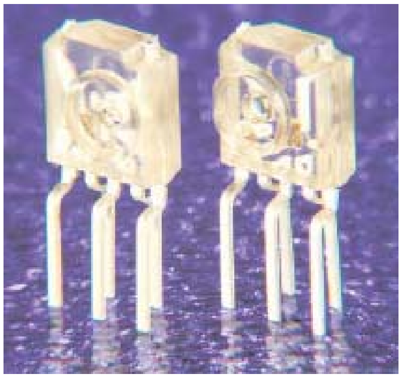


Fig. 9: Transmitter and receiver fiber optic module pair for Gb/s data links over plastic optical fiber. The transmitter contains a 665nm VCSEL

The package consists of a pair of a POF transmitter module and a receiver module. The VCSEL is encapsulated in a non-hermetic plastic material. The receiver module contains a high speed photodetector and a transimpedance amplifier. Both packages feature a molded lens to facilitate coupling to the optical fiber with high coupling efficiency and relatively large alignment tolerances.

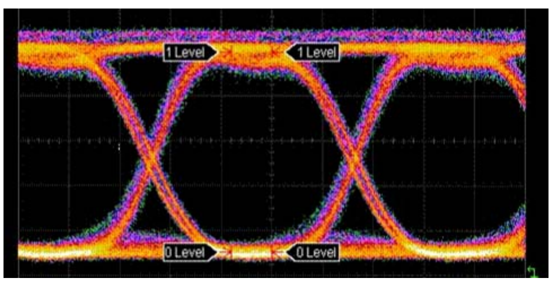


Fig. 10: Eye diagram for the transmitter fiber optic module running at 1.25Gb/s

The eye-diagram of the VCSEL transmitter module is shown in Fig. 10. The data rate is 1.25Gb/s. The eyes are clean and wide open. The red VCSEL is the key technology for POF links in the Gb/s range. As with their 850nm counterparts the red VCSEL enables low cost packaging and its emission wavelength matches the optical attenuation minimum of POF.

Reliability Studies

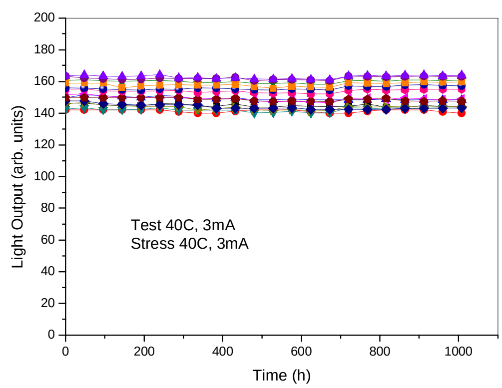
We have carried out several high temperature operating life-time (HTOL) tests with the visible VCSELs. The different test conditions are summarized in Tab. 1. Ambient temperature varies between 40^{o}C and 85^{o}C with drive currents between 3mA and 5mA. 16 units are used for each element of the stress test matrix. The devices are mounted on TO-header for easy handling.

Tab. 1: Stress matrix for HTOL test

Devices in Test (pcs)	Current (mA)		
Temp. (^{o}C)	3	4	5
40	16	16	16
60	16	16	NA
85	16	16	16

The devices operate very stable even under the highest stress conditions. No random failures have been observed. Fig. 11 shows the VCSEL output power as function of time for a few examples of the tests performed. Even at an ambient temperature of 85^{o}C with a stress current of 5mA the device degradation is quite small.

a)



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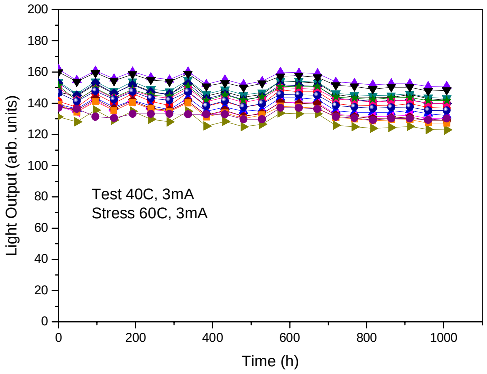

c)

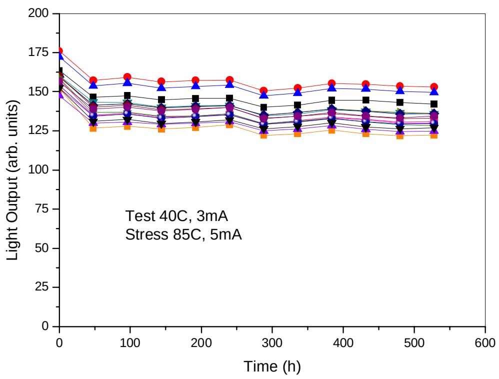

Fig. 11: High temperature over life (HTOL) test for VCSELs under various stress conditions a) 40°C, 3mA b) 60°C, 3mA, c) 85°C, 5mA. Each graph shows the light output of 16 devices under test measured at 40°C and 3mA

From the different test conditions with different ambient temperatures and current stress conditions we infer the device life time at normal operating conditions.

$$A.F = \left(\frac{I_1}{I_2}\right)^n \exp\left(\frac{E_A}{k_B}\left(\frac{1}{T_{j1}} - \frac{1}{T_{j2}}\right)\right)$$

Fig. 12: Acceleration model for VCSELs under high current (I) and high temperature (T) stress conditions. I and T are taken at operating and stress condition, respectively. E_A is the activation energy, k_B the Boltzmann constant

We use the standard aging acceleration factor model as depicted in Fig. 12 to estimate life time. The various results are compared using common statistical methods such as log-normal distribution or Weibull statistics. We have inferred a conservative estimate for the activation energy of 0.6eV. The red VCSELs described here exhibit a 1% time to failure time (1%TTF) of more than 100,000hours at normal use conditions at an ambient temperature of 40°C. To the best of our knowledge these results are far better than any previously published data [5, 6]. It demonstrates clearly that red VCSELs can be reliable and are well suited for real life applications.

VCSEL Array for Imaging Applications

Another advantage of VCSELs is that they can easily be arranged in two-dimensional arrays. For visible VCSELs this feature can be employed for various imaging applications. Figure 13 exhibits an application example of the VCSEL array used as pointing device for numbers. The same type of VCSEL could also project alpha-numeric characters.

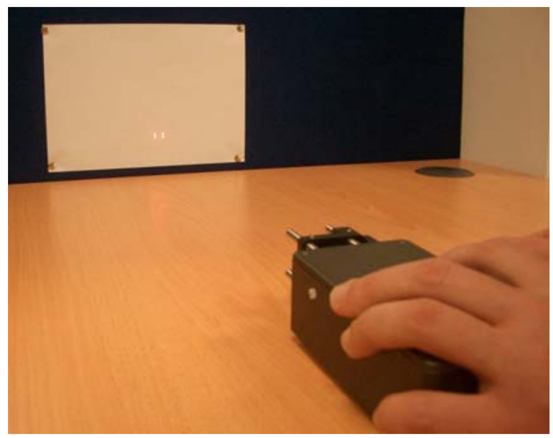

Fig. 13: Red VCSEL array for imaging applications. Even complicated shapes such as 7-segment numbers can be implemented in a visible VCSEL array

The light output of the VCSEL array is easily focused with a lens to project a clear and bright image over distances of several meters. This device contains two digits of a seven segment projection display. Figure 14 shows one segment with the various numbers from 1 to 9.

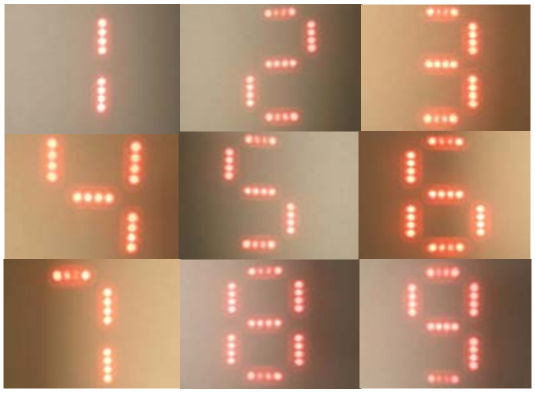

Fig. 14: Examples of the projected near field of a 7-segment VCSEL array. The VCSEL array output beam is easily collimated by a lens for long range projection. The image is very sharp.

Visible VCSEL arrays enable various kinds of image and information projection displays. VCSEL emitting in the blue and green spectrum range will enable full color projection displays in the future.

Conclusion

In conclusion, we have fabricated high quality visible VCSELs in the 650nm to 690nm wavelength range for low cost POF optical links and optical sensor applications. The threshold current of the devices is about 1mA and the output power larger than 1mW. The maximum operating temperature is beyond 60^{o}C. From aging tests we have inferred a 1%-time-to-failure (1%TTF) of the devices is over 100,000 hrs at use conditions at 40^{o}C ambient temperature.

The spectrum is single mode and highly polarized. Together with the small divergence angle of less than 10degrees this makes the devices ideal light sources for free-space and sensor applications. The high modulation bandwidth in excess of 3GHz at low operating currents of around 5 mA makes the devices also well suited for high speed short distance optical links over standard POF. The high badnwidth enables IEEE1394b S800, Gigabit Ethernet and other high speed applications over low cost POF.

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